

JPL Publication 83-67

Advanced Cogeneration Research Study

Executive Summary

S. Bluhm
N. Moore
L. Rosenberg
M. Slonski

June 1983

Prepared for
Southern California Edison Company
Through an Agreement with
National Aeronautics and Space Administration
by
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Advanced Cogeneration Research Study

Executive Summary

S Bluhm
N Moore
L Rosenberg
M Slonski

June 1983

Prepared for
Southern California Edison Company
Through an Agreement with
National Aeronautics and Space Administration
by
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Prepared by the Jet Propulsion Laboratory,
California Institute of Technology, for the
Southern California Edison Company through
an agreement with the National Aeronautics
and Space Administration.

Reference to any specific commercial product,
process, or service by trade name or manufacturer
does not necessarily constitute an
endorsement by the sponsor, U.S. Government,
or Jet Propulsion Laboratory, California
Institute of Technology.

ABSTRACT

This study provides a broad based overview of selected areas relevant to the development of a comprehensive Southern California Edison (SCE) advanced cogeneration project. The areas studied are:

- (1) Cogeneration potential in the SCE service territory
- (2) Advanced cogeneration technologies
- (3) Existing cogeneration computer models

An estimated 3700 MW_e could potentially be generated from existing industries in the Southern California Edison service territory using cogeneration technology. Of this total, current technology could provide 2600 MW_e and advanced technology could provide 1100 MW_e. The manufacturing sector (SIC Codes 20-39) was found to have the highest average potential for current cogeneration technology. The mining sector (SIC Codes 10-14) was found to have the highest potential for advanced technology.

In reviewing cogeneration technologies, JPL considered over 30 advanced systems, most of which had outputs in the range of 3 to 15 MW_e. Among currently available options, Rankine topping cycle and conventional gas turbine systems that utilize distillate and/or natural gas fuels (not solid fuels) can generate low cost electricity provided that the fuels are moderately priced (close to \$5.00 per million Btu). Rankine bottoming cycles were found to have high cost of electricity (even though the energy source is waste heat) due to high initial capital cost. Two options, with mid-term (3-5 year) potential, were found to be particularly attractive for three reasons: multi-fuel capability, low emissions, and low cost of electricity. Both systems use directly-fired gas turbine engines with heat recovery boilers. One system utilizes a pressurized fluidized bed combustor and the second utilizes an integrated, air-blown gasifier. Fuel cell based cogeneration systems utilizing air-blown gasifiers were found to have potential in the far term to provide fuel flexibility and minimal emissions at a competitive cost of electricity. The relative megawatt contribution of these and other technologies will depend on several factors, including the extent of continuing national research efforts by the U.S. Department of Energy, the Electric Power Research Institute, and the Gas Research Institute to successfully develop and demonstrate the technologies.

Approximately thirty existing cogeneration computer models were reviewed and five models were recommended for further analysis: CELCAP, COGEN 2, CPA, DEUS, AND OASIS.

FOREWORD

The contents of three separate documents comprising the series entitled "Advanced Cogeneration Research Studies" are summarized in this Executive Summary. The three documents are

- (1) Survey of Cogeneration Potential by M. Slonski (JPL Publication 83-40 Rev. A), June 1983.
- (2) An Assessment of Advanced Technology for Industrial Cogeneration by N. Moore (JPL Publication 83-66), June 1983.
- (3) Cogeneration Computer Model Assessment by L. Rosenberg, (JPL Publication 83-59), June 1983.

ACKNOWLEDGMENT

This report documents work performed by the Jet Propulsion Laboratory (JPL), California Institute of Technology, Pasadena, California, under Contract Purchase Order No. C2742911 with the Southern California Edison Company, Rosemead, California, through the National Aeronautics and Space Administration (NASA Task RE-152 Amendment 358). The work done under the contract was performed between November 1982 and June 1983.

CONTENTS

I.	INTRODUCTION	1
II.	CONCLUSIONS	1
	A. Cogeneration Potential for Existing Industries in the Southern California Edison Territory	1
	B. Advanced Cogeneration Technologies	2
	C. Cogeneration Computer Models	3
III.	ADVANCED COGENERATION TECHNOLOGY	3
	A. The Concept of Cogeneration	3
	B. Types of Cogeneration Systems	3
	C. Comparison of Cogeneration Technologies	4
	D. Recommendations	10
IV.	COGENERATION POTENTIAL IN THE SCE SERVICE TERRITORY	11
V.	COGENERATION COMPUTER MODEL ASSESSMENT	15

Tables

1.	Matrix of Cogeneration System Options Considered in the Study	5
2.	Cogeneration System Characteristics	7
3.	Cogeneration Potential for SCE Service Territory	13
4.	Cogeneration Potential by Economic Sector	14
5.	Gas Turbine Topping Cycle Parameters	14
6.	Bottoming Cycle Parameters	14
7.	Characteristics of Selected Cogeneration Computer Models	15

I. INTRODUCTION

It is the policy of the Southern California Edison Company (SCE) to devote significant corporate resources to the accelerated development of a wide variety of future electrical power options based on renewable and alternative energy resources. These include wind, geothermal, solar, fuel cells, small hydroelectric, and continued emphasis on conservation, load management, and cogeneration. By 1992 renewable and alternative firm capacity is planned to increase over 1981 levels by a factor 2.5 (from 6% to 15% of system capacity). Extensive research and development must be conducted to ensure the availability of renewable and alternative energy systems which meet economic, technical, and environmental requirements. SCE is in the process of planning and implementing many advanced technology programs. This report supports the advanced cogeneration technology program.

Cogeneration is the simultaneous production of electricity and useful heat. The attractiveness of cogeneration lies in improved efficiency of fuel utilization over that resulting from the independent generation of equivalent units of electricity and process heat.

There are two basic types of cogeneration systems: topping cycles and bottoming cycles. A topping cycle enables electricity to be generated at a high temperature immediately after the fuel is combusted. The products of combustion are then used to provide process heat, usually in the form of steam. A bottoming cycle enables electricity to be generated at a low temperature after the products of combustion have been used to make steam.

The purpose of the study is to provide a broad based overview of selected areas relevant to the development of a Southern California Edison advanced cogeneration program. The areas studied are:

- (1) Cogeneration potential in the SCE service territory
- (2) Advanced cogeneration technologies
- (3) Existing cogeneration computer models

It is essential to have an internally consistent estimate of cogeneration potential in order to verify the assumption that cogeneration represents an important energy source for the future. To realize that potential, advanced technologies must be identified and developed. Proposed cogeneration projects must be evaluated using accurate computer models.

The intent of this executive summary is to highlight the key findings of the JPL overview and to provide general direction and focus to future development of advanced cogeneration.

II. CONCLUSIONS

A. Cogeneration Potential for Existing Industries in the Southern California Edison Territory

JPL conducted a survey using probability sampling methods to estimate the potential electric power that could be produced by existing industries in the Southern California Edison territory using currently available or advanced cogeneration technology. The survey results show that 2600 MW_e could be provided using current technology and an additional 1100 MW_e could

be provided using advanced technology. The total potential is estimated to be 3700 MW_e. The uncertainty associated with these estimates can be expressed by confidence intervals. The 95% confidence interval for the estimate of total potential is 2800 MW_e to 4600 MW_e, which contains the true value with probability 0.95.

The manufacturing sector (SIC Codes 20-39) was found to have the highest potential for current cogeneration technology. The mining sector (SIC Codes 10-14) had the highest potential for advanced technology.

Companies having processes with liquid waste streams and processes with boilers had the most potential for current technology. Companies having these processes would also gain more potential from advanced technology than would companies with other types of processes.

Consumption of natural gas was positively correlated with cogeneration potential for both current and advanced technology. Surprisingly, electricity consumption showed a positive correlation with advanced cogeneration potential. The basis for this result was not fully understood, although it seems to be associated with the presence of direct fired processes.

Finally, because very few facilities had adopted cogeneration systems to date, effects of organizational differences on adoption rates could not be adequately assessed. Within the manufacturing sector, which had the greatest potential, more than half the facilities had not yet considered cogeneration. Large facilities had the greatest potential and would be the likely place to start encouraging the adoption of cogeneration.

B. Advanced Cogeneration Technologies

In reviewing cogeneration technologies, JPL considered currently available, near-term (up to 3 years), mid-term (3-5 years), and long-term (5-15 years) options.

Among currently available options, Rankine topping cycle and conventional gas turbine systems that utilize distillate and/or natural gas fuels (not solid fuels) can generate low cost electricity provided that the fuels are moderately priced (close to \$5.00 per million Btu). Rankine bottoming cycles were found to have high cost of electricity (even though the energy source is waste heat) due to high initial capital cost.

Two mid-term options were found to have costs of electricity among the lowest identified in this study. Both of these systems are based on directly-fired gas turbine engines with heat recovery boilers, which represent presently available technology. The technological advancement lies in the mode of fuel utilization by the directly-fired gas turbine engines. The lowest cost system utilizes a pressurized fluidized bed combustor (PFBC) in which biomass, refuse, coal or other suitable solid fuel is burned. The second system, having a somewhat higher cost of electricity, utilizes an integrated, air-blown gasifier unit also capable of handling coal or other suitable solid fuel. Both of these advanced cogeneration system options are capable of low emissions of nitrogen and sulfur oxides without post-combustion flue gas treatment; however, their capability to meet extremely stringent emissions standards (that are much more restrictive than those now in effect) without post-combustion treatment remains to be determined.

Fuel-cell-based cogeneration systems, utilizing air-blown gasifiers capable of handling solid fuels, were found to be available in the mid-term and to have moderately high costs of electricity. But these systems have the potential for substantial cost reduction in the long term.

C. Cogeneration Computer Models

In assessing cogeneration computer models, JPL identified and reviewed 30 existing computer models and studies. Five superior models were found to have components useful to SCE: CELCAP, COGEN 2, CPA, DEUS, and OASIS. Additional work should be done to prepare a cogeneration computer model that provides highly accurate assessments of cogeneration systems appropriate to the SCE service territory. Test cases should be run with existing models, especially COGEN 3 when it becomes available, and a detailed code analysis should be performed to enable integration of an accurate bill calculation algorithm.

III. ADVANCED COGENERATION TECHNOLOGY

A. The Concept of Cogeneration

Cogeneration is the practice of simultaneously providing thermodynamic work and useful thermal energy from the same fuel or heat source. The thermodynamic work output of a cogeneration system is usually shaft power or electricity; the thermal energy output is usually steam or hot water at a temperature high enough to be used in an industrial process or other application. Typically, a cogeneration system feeds steam and electricity into an industrial plant's distribution system for use throughout the plant.

The overall gain in the efficiency of fuel utilization resulting from cogeneration occurs because the electricity produced by cogeneration systems displaces an equivalent amount of electricity produced by a conventional utility power plant.

The attributes of advanced cogeneration systems that served as the basis for this assessment include fuel flexibility, potential for low emissions, efficiency of energy utilization, initial capital and operating costs, and technological state of development and developmental risk.

B. Types of Cogeneration Systems

Cogeneration systems are generally categorized according to the type of energy conversion device on which they are based. In this study, cogeneration options were based on either heat engines or fuel cells.

In the cogeneration systems based on heat engines, the energy source is the combustion of fuel. A portion of the energy released as heat by combustion is converted into electricity by the heat engine driving an electrical generator. Some of the remaining combustion energy is utilized to provide useful thermal energy, and some is lost through system inefficiencies and in the flue gas. All heat engines carry a working fluid through a thermodynamic cycle in order to convert thermal energy into thermodynamic work and are, therefore, subject to the Carnot limit for attainable efficiency. Heat engine energy conversion systems are generally classified according to the type of thermodynamic cycle on which they operate. Thermodynamic cycles considered in this study are the Rankine, Brayton, and Stirling.

Cogeneration systems based on heat engine energy conversion systems may be of either the topping cycle or bottoming cycle configuration. In topping cycle systems, the combustion of fuel provides thermal energy directly to the heat engine. The laws of thermodynamics require that some heat be rejected by the heat engine, and in cogeneration systems this rejected heat is then used in an industrial plant or process. The heat rejected from some engines is at a relatively high temperature, approximately 800 to 1000°F for combustion turbine exhaust gases.

In bottoming cycle cogeneration systems, the heat source supplies thermal energy directly to the industrial process. Thermal energy rejected by the industrial process is then supplied to the heat engine for electricity production. The heat source is usually a flue gas stream or process fluid stream at a much lower temperature than that of the combustion heat source of a topping cycle system. Operating at low temperature requires a much larger heat exchanger (adding to capital cost) and reduces the efficiency of conversion of thermal energy to electricity. In this study, only Rankine cycle cogeneration systems were considered in both topping cycle and bottoming cycle versions.

Unlike heat engines, fuel cells do not make use of the thermodynamic cycle energy conversion process. Instead, fuel cells convert a fuel and an oxidizer to electrical power by means of an electrochemical reaction that takes place within the fuel cell elements. The theoretical electrical output of a typical electrochemical fuel cell is in excess of 80% of the fuel energy; however, thermodynamic irreversibilities associated with practical fuel cell operation reduce the electrical conversion efficiency to about 40% of the fuel energy. Fuel cells have a high overall energy utilization efficiency because the heat produced in the cell stack is recoverable for use in a cogeneration system.

C. Comparison of Cogeneration Technologies

The cogeneration system options analyzed in this study are shown in Table 1. The advanced systems were identified through a comprehensive survey of energy technology and are intended to include those systems that have potential for use in industrial applications in the foreseeable future.

The analysis of the cogeneration system options included the identification of major components, an assessment of their technological status and potential for improvement, a consideration of their fuel flexibility and emissions characteristics, a thermodynamic analysis to estimate cogeneration system performance, and projections of installed capital costs.

The estimates of performance and cost were then used to calculate a representative cost of electricity for each cogeneration system option. The projections for installed capital costs for the cogeneration systems are direct costs and do not include interest on funds during construction, contingencies, tax credits, and other items that can significantly impact the cost of acquiring and owning a cogeneration system. Therefore, the costs of electricity determined for the cogeneration system options are for relative comparisons only and are not intended to reflect the actual cost of cogenerated electricity.

Table 1. Matrix of Cogeneration System Options Considered in the Study
(X indicates combination considered)

		Energy Conversion System				
Energy Source/ Mode of Utilization	Rankine Cycle Topping Bottoming	Gas Turbine Engine	Reciprocating Engine	Stirling Engine	Fuel Cell	
Fuel Oil (Distillate)	X ^h	X ^h	X ^b	X ^h	X ^e	
Natural Gas			X ^c		X	
Direct Coal	X	X	X ^d			
Gasification (Multi-fuel)		X ^f	X ^{b, f}			
Atmospheric Fluidized Bed (Multi-fuel)	X	X ^a	X			
Pressurized Fluidized Bed (Multi-fuel)			X			
Process Waste Heat		X				
Solar	X					

^aThe gas turbine engine was analyzed in an additional indirectly-fired configuration not shown in this table; see Section 4.2.2 of the Cogeneration Technology report.

^bReciprocating engines were analyzed in a conventional version and in an advanced, uncooled version.

^cConventional reciprocating engine only.

^dAdvanced, uncooled, reciprocating engine only.

^eFuel cells of both the phosphoric acid type and the molten salt type were analyzed.

^fAir-blown gasifier only.

^gBoth air-blown and oxygen-blown gasifiers were analyzed.

^hDual fuel system for both natural gas and distillate.

(1) Present Cogeneration Technology

The characteristics of the four types of presently available cogeneration systems are shown in Table 2. These characteristics are based on system specifications and equipment costs as provided by manufacturers and on thermodynamic analyses to establish system performance. The costs of electricity (COE) shown in Table 2 were calculated at fuel costs of \$1.25 and \$5.00 per million Btu. The Rankine topping cycle system and the gas turbine engine system have costs of electricity significantly less than that of the reciprocating engine system. The reciprocating engine does not lend itself well to cogeneration because the heat lost to the engine's cooling system is not available to raise steam at a sufficiently high pressure. The higher capital cost of the reciprocating engine system also contributes to its relatively high cost of electricity. The Rankine bottoming cycle cogeneration system has the highest COE due to its high capital cost, despite the fact that the cost of the industrial steam boiler was not included in this system's capital cost estimate.

(2) Advanced Cogeneration Technology

State of Development. The systems shown in Table 2 represent vastly differing states of technological development; for instance, the atmospheric fluidized bed/Rankine (AFB/R) cogeneration system is nearing commercial status while the molten carbonate fuel cell system is an advanced concept based on laboratory work with molten salt fuel cell stacks. Hence, the uncertainty in the estimates of cost and performance varies greatly among the systems, as does the risk of failure in achieving expected system cost and performance characteristics.

The technological state of development of the advanced cogeneration systems may be categorized as near-, mid- or far-term, as designated in Table 2. The near-term category includes those systems in advanced stages of commercial demonstration which are nearing commercial readiness; the AFB/R system in the relatively small size useful to most cogenerators is a near-term system. The mid-term category encompasses those systems whose major components have been extensively tested at the pilot plant stage in configurations similar to those required by operational cogeneration systems. The mid-term category also includes systems whose components would represent an improvement in existing systems that extends beyond the normal practice of modifying present designs. The far-term designation applies to systems in an early stage of development where basic performance and operating parameters, component configurations, and materials of fabrication are being defined. The far-term systems presuppose that ongoing research and development work will result in energy conversion systems with the projected performance and cost characteristics.

The mid-term systems shown in Table 2 include the pressurized fluidized bed/gas turbine (PFB/GT) system, the air-blown gasifier/gas turbine (ABG/GT) system and the ABG/phosphoric acid fuel cell system. PFB/GT systems have received extensive development in the past ten years, but additional work remains, particularly in satisfactorily integrating PFB units and gas turbine engines to achieve acceptable turbine service life. Atmospheric pressure coal gasifiers have been commercially available for years, as have larger high pressure units. However, an air-blown gasifier operating at 8 to 10 atmospheres pressure that is suitable for integration with a gas turbine engine or fuel cell for the industrial cogeneration application in the 10-MW power range

Table 2. Cogeneration System Characteristics

Cogeneration System Type	State of Development	Fuel Flexibility	Cost of Electricity mills/kW-h	Long-Term Potential for Performance Improvement and Cost Reduction		
				NA ^c \$5.00	Low Low	
Rankine Topping Oil/Gas/Fired Boiler Atm. Fluidized Bed	Present Near-term	Dist. ^a , NG ^b Solid	NA ^c 76	58	Low	
Rankine Bottoming	Present	Stack Gas Waste Heat	100	180	Low	
Gas Turbine Engine Systems						
Conventional	Present	Dist., NG	NA	51	Low	
Press. Fluidized Bed	Mid-term	Multi-fuel	52	72	Limited	
Press. Air-Blown Gasifier	Mid-term	Multi-fuel	55	82	High	
Atm. Fluidized Bed	Mid-term	Multi-fuel	78	109	Low	
Reciprocating Engine Systems						
Conventional	Present	Dist., NG	NA	102	Low	
Conventional	Mid-term	Multi-fuel	87	126	Low	
Air-Blown Gasifier	Far-term	Coal	65	85	Limited	
Ceramic Engine, Direct Coal Injection						
Stirling Engine Topping						
Conventional	Mid-term	Dist., NG	NA	89	Low	
Atm. Fluidized Bed	Mid-term	Solid	79	98	Limited	
Solar Point-Focusing Rankine	Mid-term	NA	430	330	Limited	
	Far-term	NA	200	95	High	
Fuel Cell Systems						
Phosphoric Acid Cell, Press. Air-Blown Gasifier	Mid-term	Multi-fuel	70	85	Limited	
Molten Carbonate Cell, Press. Air-Blown Gasifier	Far-term	Multi-fuel	53	69	High	

^aDist. = Petroleum distillate.^bNG = Natural gas.^cNA = Not applicable.

is not available. Several candidate system designs are available for consideration, but further development work is required. The differing requirements for coal gas cleanup between gas turbine engines and fuel cells may have a significant impact on gasifier system configuration and cost.

The far-term systems shown in Table 2 are the direct coal injection/ceramic reciprocating engine and the ABG molten carbonate fuel cell. Both the ceramic reciprocating engine and the molten fuel cell have been operated in experimental configurations. These two energy conversion systems represent the introduction of new, high-temperature materials technology into energy conversion systems.

Emissions and Fuel Flexibility. The advanced cogeneration systems of Table 2 make use of four different generic techniques of fuel utilization: fluidized bed combustion, air-blown gasification, coal extrusion, and conventional diffusion flame combustion. A Rankine cycle system, two of the gas turbine engine systems, and a Stirling engine system incorporate fluidized bed combustion to simultaneously achieve emissions control and solid fuel burning capability. The fuel cell systems, a gas turbine engine system, and a reciprocating engine system feature air-blown gasifiers which produce fuel gas from a raw feed stock of carbonaceous material such as biomass, coal, or refuse. The fuel gas would be cleaned of contaminants prior to combustion in the heat engines or electrochemical reaction in the fuel cell. The uncooled, ceramic reciprocating engine is fueled by coal that is directly injected into the engine's cylinders by means of an extrusion process that plasticizes the coal. The conventional systems of each type burn natural gas and liquid fuels. Emissions control for all the systems could be augmented through exhaust gas treatment, including sulfur removal and catalytic reduction of nitrogen oxides if necessary.

The advanced systems differ significantly in approach to emissions control. The AFB systems would probably require flue gas cleanup systems for both sulfur and nitrogen oxides in order to meet the more stringent air pollution rules. In contrast, the PFB system has demonstrated that virtually all of the fuel sulfur can be captured in the bed sorbent material, and PFB units have also shown extremely low levels of nitrogen oxides emissions. The coal gasifier systems are dependent on cleanup of contaminants in the fuel gas stream produced by the gasifier in order to achieve emissions control. Gas cleaning measures for the fuel cell system would depend on the allowable amounts of feed gas contaminants. Nitrogen oxides are not formed in any appreciable amounts in the fuel cell system's electrochemical energy conversion process, and only a small amount of fuel is consumed in the system's burner at a low combustion temperature. Consequently, nitrogen oxides emissions are not a problem with the fuel cell systems.

The advanced cogeneration systems using fluidized bed or gasifier units have the potential to accommodate a variety of fuels. Additional burner units for liquid and gaseous fuel could be fitted to the fluidized bed systems, and the gasifier systems may, with development, accommodate liquid or gaseous fuel. Advanced reciprocating engines could be fitted with liquid fuel injection systems and gaseous fuel induction systems similar to those of presently available dual fuel engines.

Cost of Electricity. The cost of electricity produced by cogeneration systems is primarily determined by the system's capital cost, overall efficiency of energy usage, and the cost of fuel consumed by the cogeneration

system. As the costs of natural gas and distillate fuel escalate, the cost of electricity produced by the presently available cogeneration systems increases substantially. At these higher costs of electricity, an additional capital investment to enable the use of less expensive fuel such as biomass, coal, or refuse would be justified. The presently available technology for utilization of solid fuel is restricted to the Rankine topping cycle cogeneration systems. These coal/solid fuel burning Rankine cycle cogeneration systems have a comparatively high capital cost; as a result, the cost of electricity produced by such systems is competitive with electricity purchased from the utility company only in limited circumstances. For example, a relatively large industrial plant may achieve economy of scale sufficient to make coal-fired cogeneration attractive, or the availability of refuse or a waste product to be used as fuel may justify an investment in a Rankine cycle cogeneration system.

Certain advanced systems for industrial cogeneration considered in this study offer the potential for use of less expensive solid fuels such as biomass, refuse, or coal in systems whose overall efficiency of energy utilization and capital cost are such that attractive costs of electricity are obtained in moderately sized systems suitable for use in typical industrial plants. An additional capital investment in such systems could likely be justified, particularly in an era of expensive natural gas and distillate fuel. The costs of electricity for advanced cogeneration systems are shown in Table 2 for fuel costs of \$1.25 and \$5.00 per million Btu. The pressurized fluidized bed/gas turbine engine system has the lowest cost of electricity at 52 mills/kW-h at a fuel cost of \$1.25/million Btu. The systems of Table 2 that have electricity costs of from 50 to 60 mills/kW-h when burning solid fuel or coal at $\$1.25/10^6$ Btu include the air-blown gasifier/gas turbine, the pressurized fluidized bed/gas turbine, and the air-blown gasifier/molten carbonate fuel cell. These advanced cogeneration systems would be economically competitive with presently available cogeneration systems fueled by natural gas or distillate at current prices. Since biomass, coal, and other solid fuels are not expected to undergo long-term price escalation to the extent of natural gas and petroleum derived fuels, the real cost of electricity produced by such advanced cogeneration systems would be expected to remain relatively stable.

Long-Term Potential for Performance Improvement and Cost Reduction.

The long-term potential for improvement in performance and/or cost of cogeneration systems is categorized in Table 2 as low, limited, or high. This categorization is based on an assessment of the present state of the technologies on which the cogeneration systems are based and of intrinsic characteristics that may limit a particular technology.

The Rankine cycle energy conversion systems are fundamentally quite mature and are likely to undergo only marginal evolutionary improvements in performance and cost. The AFB boilers will benefit from further improvements in durability and will likely decrease in capital cost. However, their position relative to the other advanced cogeneration systems is not likely to change.

Gas turbine engines are likely to continue to experience improvements in performance and specific power brought about by higher temperature materials and improved designs. The air-blown gasifier/gas turbine engine cogeneration system (ABG/GT) can experience the full advantage of such improvements, providing that nitrogen oxides control technology keeps pace with the increased temperature capability. In contrast to the ABG/GT, the

fluidized bed/gas turbine systems are limited in operating temperature by the techniques of sulfur capture and retention in the fluidized bed. While the lower operating temperature tends to reduce gas turbine engine efficiency, the overall efficiency of energy utilization is not adversely affected because the otherwise lost energy is recovered as industrial process heat. The atmospheric fluidized bed/gas turbine system suffers the disadvantages of a larger and more costly fluidized bed unit, due to operation at atmospheric pressure and a lower operating temperature due to the more highly stressed high-temperature heat exchanger.

The uncooled ceramic reciprocating engine is a major advancement in heat engine technology. The cogeneration system based on the uncooled engine overcomes a major disadvantage of the conventional reciprocating engine in that the quantity of heat available to generate industrial process steam is increased about two-fold. However, the overall efficiency of energy utilization does not match that of the gas turbine and fuel cell systems. Unless the capital cost of the reciprocating engine is reduced by the advent of ceramic materials, the gas turbine and fuel cell based systems will continue to be preferred for industrial cogeneration.

The Stirling engine cogeneration system has limited long-term potential because, relative to the other systems, its capital cost is high and no credible approach to adequate cost reduction is extant. The system cost problem is more severe in the atmospheric fluidized bed Stirling system due to the additional cost of the AFB unit.

The solar point-focusing Rankine cogeneration system requires a further capital cost reduction before it is competitive. Table 2 shows the solar cogeneration system in a mid-term and a far-term version, the capital cost of the far-term version being one-half that of the mid-term version. With such a capital cost reduction, the far-term system has a cost of electricity among the higher cost options with fuel at \$5.00/10⁶Btu. When displacing more expensive fuel, the far-term solar cogeneration system will be more attractive.

Continued development of fuel cell technology could lead to substantial system-level improvements in durability, reliability, lifetime, and capital cost. The performance of the phosphoric acid fuel cell is established, and further breakthroughs in electrochemical energy conversion technology seem unlikely. But improvements in fuel cell systems, primarily reductions in capital cost coupled with extended service life, could improve their relative position in the ranking of advanced cogeneration systems. The far-term fuel cell option, molten carbonate cell/air-blown gasifier, has the potential to be the principal component in an extremely attractive industrial cogeneration system.

D. Recommendations

The following recommendations are offered for the technological advancement of industrial cogeneration systems:

A detailed assessment of the applicability of pressurized fluidized bed combustors to gas turbine engines in the 3 to 15 megawatt range should be carried out. Such an assessment would include an in-depth investigation of alternative PFBC designs, their costs and performance, and their suitability for integration with the smaller gas turbine engines.

A parallel study of air-blown gasifiers operating at 8 to 12 atmospheres pressure should also be performed. In general, gasification technology is quite mature, and several types of gasifiers are commercially available; but integration of a pressurized, air-blown gasifier with gas turbine engines in the size range under consideration here is not a developed technology. The recommended assessment of air-blown gasifier technology for advanced industrial cogeneration would focus on identifying a design for a high-efficiency, pressurized unit suitable for integration with gas turbine engines in the 3 to 15 megawatt range. The study should encompass unique methods of fuel sulfur removal, including in-situ sulfur capture, perhaps in a fluidized bed or moving bed gasifier; and, as with the PFBC unit, fuel feeding and ash removal systems for the smaller units should be given particular attention in a search for innovative improvements.

The above described study of pressurized, air-blown gasifiers should also consider the integration of such units with fuel-cell-based cogeneration systems. Fuel cells have much more stringent requirements for fuel gas composition than do gas turbine engines, and the effects of solid fuel composition on gas cleanup and on fuel gas composition must be considered.

An in-depth assessment of the nitrogen oxide emissions characteristics of gas turbine engine combustion of low-Btu fuel gas should be performed. Recent reports in the open literature indicate that formation of nitrogen oxides in low-Btu gas combustion may be more prevalent than expected. The status of low-Btu gas combustion technology for gas turbine engines should be ascertained relative to emission standards expected in the Southern California area.

IV. COGENERATION POTENTIAL IN THE SCE SERVICE TERRITORY

To estimate the cogeneration potential of existing industries in the SCE service territory, a telephone survey was conducted using probability sampling methods. The methodology comprised establishing a sampling frame that represents the population of heat producers within the SCE service territory and drawing a sample. A questionnaire was developed and administered to the sample.

The population comprised all facilities in the SCE service territory that have high rates of thermal energy production; that is, facilities generating sizeable amounts of heat through ovens, boilers, furnaces, or other means. Criteria were developed for quantifying the terms "high rates" and "sizeable" that were used to construct the sampling frame. Because it was prohibitive to construct a complete list of all facilities in the population, the sampling frame was used to simulate the population; it contained facilities, or sampling units, that represented the population. In practice, facilities were included in the sampling frame on the basis of whether or not they used electricity, natural gas, or fuel oil that matched or exceeded the established criteria. The best data available to construct the sampling frame consisted of a list of SCE electric customers and a list of facilities that have been issued boiler permits by the South Coast Air Quality Management District (AQMD).

Criteria were developed for including facilities in the sampling frame and subdividing it into two segments, large facilities and medium facilities. The sampling frame was segmented into large and medium facilities to ensure

that the very large users would be sampled. Small facilities were not included because the sum of the potential from this group was considered negligible.

The principal factor used for dividing the SCE list between large and medium facilities was the percentage of the total demand. The large facilities account for about 15% of the total MW_e demand for facilities in the sampling frame. A comparable value based on Btu/h was then established for the AQMD list. Similarly, the lower bound of 1 MW_e demand was set by SCE, and a comparable value based on Btu/h was established for the AQMD list.

Once each list had been divided into large and medium facilities, they were compared to eliminate duplication. The facilities included in the AQMD list that were not located in the SCE service territory were also eliminated; this included facilities in the City of Los Angeles and regions serviced by other utilities. The initial sampling frame included a total of 31 large facilities, 11 from the SCE list and 20 from the AQMD list, and 1093 medium facilities, 740 from the SCE list and 353 from the AQMD list. Finally, adjustments were made for listing errors (duplication, incorrect addresses, etc.), and the final sampling frame included 25 large facilities and 984 medium facilities, which were used as multipliers for the population estimators.

The principal form of bias in the sampling frame arose because cogeneration requires heat processes, not electric processes, and the primary list of facilities was based on electric consumption. An unbiased sampling frame would include all electric users, natural gas users, and fuel oil users. Other biases in the sampling frame arose because the AQMD list was used to represent natural gas and fuel oil users, but there were some problems associated with the list. In particular, the list was a few years old and not complete; this resulted in the exclusion of facilities in the northern areas of the territory that had low electricity consumption but high thermal usage.

The primary objective of the survey was to estimate the potential electric power that could be produced in the SCE service territory using cogeneration technology. The estimate was to be subdivided into three categories:

- (1) That which may be generated using conventional technology
- (2) The additional amount that could be generated using advanced technology
- (3) The thermal energy that did not have potential for cogeneration

Current cogeneration potential is the electricity that could be generated in the industrial/commercial sector using conventional, off-the-shelf equipment. Advanced cogeneration potential is the additional electricity that would be generated if advanced technology, available in 5 to 15 years, were used in place of the current technology. The potential that is not feasible is from heat sources below 300°F. The cogeneration potential was calculated separately for both large and medium facilities.

The results of the survey are summarized in Table 3. Based on the number of facilities in each segment, the total cogeneration potential for the SCE service territory is estimated to be 3700 MW_e . The uncertainty associated with this estimate can be expressed by a confidence interval. The 95% confidence interval for the estimate is 2800 MW_e to 4600 MW_e , which contains

the true value with probability 0.95. The potential that was considered not feasible is 1600 MW_t, with a 95% confidence interval of 1200 MW_t to 2000 MW_t.

Table 3. Cogeneration Potential for SCE Service Territory

Category	All Facilities	Large Facilities	Medium Facilities
Current Technology, MW _e	2600 \pm 700	1100	1500 \pm 700
Advanced Technology, MW _e	1100 \pm 300	300	800 \pm 300
TOTAL	3700 \pm 900	1400	2300 \pm 900
Not Feasible, MW _t	(1600 \pm 400)	700	900 \pm 400

The breakdown of the cogeneration potential by economic sector is presented in Table 4. While the manufacturing sector has the highest average potential for current technology, the mining sector has the most potential for advanced technology.

The estimates of cogeneration potential are subject to two different types of errors, reporting errors and calculation errors. Reporting errors occur because of inaccurate or incorrect answers, missing or insufficient data, and inconsistencies among data. An attempt was made to resolve discrepancies and fill in missing data by making follow-up telephone calls or using reasonable engineering judgment when possible. Calculation errors are due primarily to biases in the methodology that may favor one type of cogeneration system over another, as well as the characteristics assumed for each type of system. It should also be noted that the list of facilities did not cover the entire SCE service territory, as mentioned earlier in discussing the AQMD list.

Technical characteristics used for distinguishing between current and advanced technology were source of heat, efficiency, and exhaust temperature. For current technology gas turbine topping cycles, efficiencies were assumed to range from 20% to 37% depending on unit size (0.5 to 20.0 MW_e); exhaust temperatures ranged from 900 to 1200°F. For advanced technology gas turbine topping cycles, efficiencies were assumed to range from 35% to 40% and exhaust temperatures ranged from 1200 to 1500°F over the same unit size range (0.5 to 20.0 MW_e). These values are summarized in Table 5. Values assumed for current and advanced technology bottoming cycles are presented in Table 6.

In addition to technical factors such as temperature and efficiency, it is recognized that there are economic and institutional factors that affect the adoption of cogeneration by industry. These include ownership, buy-back rates, price of alternative fuels, pollution restrictions, etc. However, these factors were not addressed in this study.

Table 4. Cogeneration Potential by Economic Sector (Average MW_e)

Sector	Standard Industrial Classification (SIC) Code	With Current Technology	With Advanced Technology	Number of Facilities
Manufacturing	20-39	24.9	6.1	26
Mining	10-14	10.6	9.3	6
Transportation	40-49	5.0	2.5	5
Government	91-97	2.4	1.9	4
Other*	50-89	0.7	0.6	9

*Includes trade, finance, and services.

Table 5. Gas Turbine Topping Cycle Parameters

Size Range, MW _e	Current Technology Efficiency, %	Exhaust Temp., °F	Advanced Technology Efficiency, %	Exhaust Temp., °F
0.5	20	900	35	1200
4.0	27	1000	37	1500
20.0	37	1000 - 1200	40	1500

Table 6. Bottoming Cycle Parameters

Size, MW _e	Source Temperature, °F	Working Fluid	Efficiency, %
0.5 and up	400 to 1000	Steam	14-36
0.5 - 1	300 to 350	Organic Fluid	9 (Current) 15 (Advanced)
2 and up	300 to 350	Organic Fluid	12 (Current) 16 (Advanced)

V. COGENERATION COMPUTER MODEL ASSESSMENT

The purpose of this task is to assess cogeneration computer simulation models in order to recommend the most desirable models or their components for use by SCE in evaluating potential cogeneration projects. Approximately thirty models and studies were reviewed, and five models were recommended for further analysis as summarized in Table 7.

Table 7. Characteristics of Selected Cogeneration Computer Models

Model	Major Characteristics
CELCAP (Naval Civil Engineering Laboratory)	Stored data on steam turbines, combustion turbines, diesels; thermal or electrical dispatch; available for no charge; Navy will run sample cases at no charge.
COGEN 2 (Mathtech)	Stored data on steam turbines, gas turbines, diesels, fuel cells; linear programming optimization; includes IBM software at \$1200 to \$1400/month; will make sample run if SCE pays for costs; COGEN 3, for EPRI's Team Up project, will be machine independent.
CPA (Southern California Gas Co.)	Stored data on steam turbines, gas turbines, reciprocating engines, combined cycle; thermal or electrical dispatch, base load, peak shaving, total energy; Southern California Gas will run it for a fee; will run sample cases at no charge.
DEUS (General Electric)	Stored data on steam turbines, coal gas combined cycle, fuel cells, gas turbines, diesels; thermal and economic dispatch; done for EPRI; operational on JPL computer.
OASIS (Argonne National Laboratory)	Electrical or thermal dispatch; can do hourly matching for a year; optimizes; utility representation not very detailed; still under development for DOE.

The above models appear to be superior when compared to the cogeneration model requirements defined for this study, which included (1) accurate technical and economic representation of the user's system both with and without cogeneration; (2) accurate representation of the utility rate structure; (3) straightforward operation; and (4) availability to the SCE technical staff at a reasonable cost. With the exception of OASIS, none of the models have an hourly matching algorithm integrated with the methodologies necessary for accurate calculation of electric bills. Instead, a "sample period" approach is used. JPL calculations suggest that this approximation introduces an unnecessary error into the analysis. A JPL code, which provides precise calculation of electric bills based on SCE rates, is available and could be used in conjunction with one of the five preferred models.